Closeout Presentation

Director's CD-1 Review of the Muon g-2 Project

July 23-25, 2013

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Executive Summary

The Muon g-2 experiment at Fermilab proposes to measure the anomalous magnetic moment of the muon to an unprecedented level of precision, targeting a measurement uncertainty of 0.14 parts per million, or a factor of four or more above the world's current best measurement by BNL E821. In conjunction with steady improvements in the theoretical calculations, this precision measurement offers one of the most sensitive tests of the Standard Model, and a powerful potential window into new physics.

This Fermilab review is to assess whether the Muon g-2 Project has met the requirements for DOE Critical Decision 1 (CD-1), "Approve Alternative Selection & Cost Range", as specified in DOE Order 413.3B. The Project received CD-0 on September 18, 2012, and is scheduled for a CD-1 review on September 17-18, 2013.

The Project consists of five WBS Level 2 systems, and the Project Office personnel and Level 2 and Level 3 managers are in place. The g-2 Collaboration consists of 150 collaborators from 34 institutions, half of which are based in 7 foreign countries. It consists of both E821 experimenters and new collaborators. The Project effectively builds on the experience of E821, utilizing much of the hardware from that experiment, most notably the muon storage ring. The close collaboration between the Project and the Collaboration has facilitated the transfer of lessons learned from E821, which have been effectively integrated into their designs and project planning. This has resulted in a design that is quite mature for this stage in the Project.

The Project team is strong and highly motivated, containing many members with a deep understanding of the detector, the accelerator, the experimental and technical challenges, and the physics, and is capable of successfully executing the Project. The position of Deputy Project Manager is not planned for after CD-3 approval. The Committee believes this position to be an important one for the success of the Project, and that appropriate plans should be made to find a suitable replacement.

The Project is funded by the DOE via project funds and a $2.5M Early Career award, and by the NSF through a recently awarded $3.5M Major Research Instrumentation (MRI) grant. The Early Career award and MRI grant support the detectors, electronics, and data acquisition. The Project presented a base cost estimate for the DOE portion of $32.8M. The Committee finds this estimate to be reasonable and complete. A bottom up contingency of $9.5M based on the maturity of the design was presented. An analysis of the risk-based contingency yielded a risk contingency range of $0.0M - $6.1M. The resulting cost range presented was $42.3 - $48.4M. Taking into account the current maturity of the cost and schedule, the Committee believes a range of $39.6M – $49.4M more accurately encompasses the possible cost outcomes of the Project with high probability.

The Project has developed a resource loaded schedule in PRIMAVERA and has begun using COBRA, which will be implemented to track costs and earned value. Project completion is currently projected for Q3FY16, with CD-4 estimated for 4QFY2017. Drafts of all required project documentation are in place, will well support the cost and

schedule development required for CD-1, and provide the proper foundation for an eventual baseline.

The success of the g-2 experiment depends on the integration of several Muon Campus AIP/GPP projects with the g-2 Project, and their successful completion. The Laboratory is to be commended for recognizing the complexities involved, and having proactively taken measures to identify and implement appropriate means of addressing them. Continued vigilance on the part of both the Laboratory and the Project will be required in order to ensure the success of this arrangement.

The Committee believes the Project should proceed to its CD-1 review after addressing the recommendations contained in this report.

1.0 Introduction

A Director's CD-1 Review of the Muon g-2 Project was held on July 23-25, 2013 at the Fermi National Accelerator Laboratory. The object of this review was to assess if the project meets the Critical Decision 1 (CD-1) "Approve Alternative Selection & Cost Range" CD-1 requirements as specified in DOE O 413.3B. Additionally, the committee reviewed the progress of the recommendations from the Director's Impendent Conceptual Design Review conducted on June 5-7, 2013. The charge included a list of topics and specific questions to be addressed as part of the review. The assessment of the Review Committee is documented in the body of this closeout presentation.

Each section in this closeout presentation is generally organized by Findings, Comments and Recommendations. Findings are statements of fact that summarize noteworthy information presented during the review. The Comments are judgment statements about the facts presented during the review and are based on reviewers' experience and expertise. The comments are to be evaluated by the project team and actions taken as deemed appropriate. Recommendations are statements of actions that should be addressed by the project team. The remainder of this presentation has the answers to the review charge questions.

The Muon g-2 Project is to develop a response to the review recommendations and present it to the Laboratory Management and regularly report on the progress during the Project's Project Management Group Meetings (PMGs) and at the Performance Oversight Group (POG). The recommendations will be tracked in the iTrack system where progress to closure will be tracked.

2.0 Technical

2.1 Accelerator

Primary Writers: Mike Syphers, Paul Derwent

Contributors:

Findings

- The accelerator portion is roughly 60% of the overall g-2 project.
- Much of the accelerator hardware for the project has been obtained through the re-purposing of existing beam line magnets, power supplies, and instrumentation generated from the decommissioning of systems used for the Tevatron program.
- The existing target, Lithium lens and pulsed magnet used for antiproton production have been demonstrated to be adequate for use for pion production at 3.1 GeV/c for delivery to g-2.
- Yield studies are planned for this year to verify the use of the existing target station for g-2.
- The Li Lens has been tested at an average pulse rate of 12 Hz, the same average rate as for g-2. However, g-2 will require bursts at 100 Hz. ANSYS modeling of the lens was performed to simulate the 12 Hz running conditions of the tests and agrees well with the test results. ANSYS modeling of the burst mode of operation showed no significant stress to the system, thus qualifying the use of the existing lens for g-2. The 12 Hz testing ran for 70M pulses of the lens.
- The Li Lens power supply design to incorporate the 100 Hz bursts for g-2 is well advanced including detailed SPICE modeling.
- The Pulsed Magnet (PMAG) of the existing target system will be re-used for g-2. There are 3 working spares available. The PMAG power supply will be upgraded, using a design similar to an existing power supply used for an injection kicker in the 15 Hz Booster synchrotron at Fermilab.
- The Beam Dump of the target station has a known water leak, which needs to be fixed. Based on ALARA principles, a new 80kW dump of the same design will replace the existing dump.
- The use of the Delivery Ring to stretch out the path length for the pion beam (4 revolutions is the plan) creates a very long decay channel and allows for the separation of the protons from the muons -- enabling proton removal-- and results in an ultra-pure muon beam for g-2.

- In addition to the target station upgrades, other modifications planned as part of the project include modifications to the final focus, acceptance of the beam line after the target, injection/extraction modification into the Delivery Ring, and controls and instrumentation for low-current secondary beams.

- Risks have been identified for the accelerator portion of the project and entered into the Risk Registry. Major items include impacts of Mu2e shielding in D30 straight section on necessary g-2 hardware; cost/schedule risk associated with installation due to congestion and complexity in D30 and M3 beam line; and pulsing of the Li lens at 12 Hz, though this appears to be retired.

- The optics design includes a reconfiguration of the target focusing that produces a spot size at 8 GeV equal to that during antiproton running at 120 GeV.

- The optics design and layout of the M5 beam line is flexible enough to incorporate a better inflector design should that become available.

- A redesign of the M2/M3 crossover region has been envisioned conceptually that could save ~ $0.5-1.0M.

- Bases of Estimate exist with links to a variety of back-up documents.

- The laboratory Muon Program is a main focus of the laboratory's effort over the next decade. The g-2 project has strong interdependencies on the Muon Campus program, a mix of Accelerator Improvement projects and General Plant projects that are funded through Accelerator operations. The project is able to take advantage of the integrated planning to reduce project costs but also has risks associated with work outside the project control. The interdependencies are managed through a set of interface milestones and requirements documents, which are under change control and are approved by the interested parties.

Comments

- The accelerator design is highly developed for CD-1.

- The interaction between the project and the AIP/GPPs for the accelerator work often generates some confusion about what items are on- or off-project. Work in the D30 straight section offers a good example. The team understands this and continues to make progress toward making clear statements to reviewers, but needs more polishing.

- The ability to reuse the AP0 target system and infrastructure is a very positive outcome for the experiment, an outcome that was in question a few years ago. The project is to be commended on its pursuit in understanding this system and to verify its applicability.

- The incorporation of multi-turn operation of the Delivery Ring produces much higher purity of muon beams and permits higher rates to experiment. This is a clear example of value-added engineering.

- The accelerator group is operations-centric and hence value engineering is done as a regular part of the process. They are very good at estimating and mitigating risk to the project and its components. The group should make an effort to expand upon these value-engineering successes during their presentations.

- The investigation into the redesign of the M2/M3 crossover region with a possible savings of ~0.5-1.0M is encouraged.

- The Accelerator Controls and Instrumentation effort includes phones, Ethernet, FIRUS, ODH monitoring, etc. in support of MC-1. The question arises whether this should be incorporated into a more appropriate AIP/GPP. If this effort remains on-project, statement of such assumptions should be made early in the overview talks/discussions at future reviews.

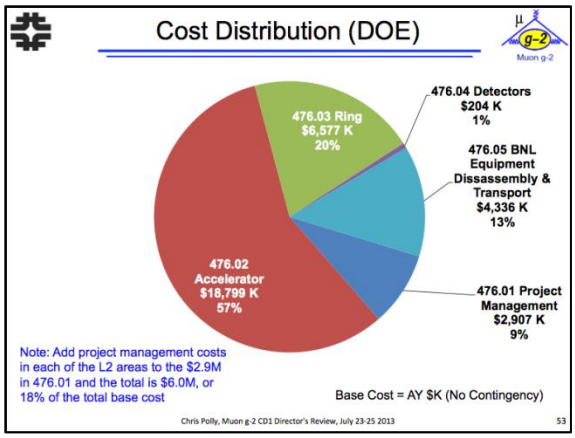
- Recommendations from the June 2013 ICDR are being addressed appropriately.

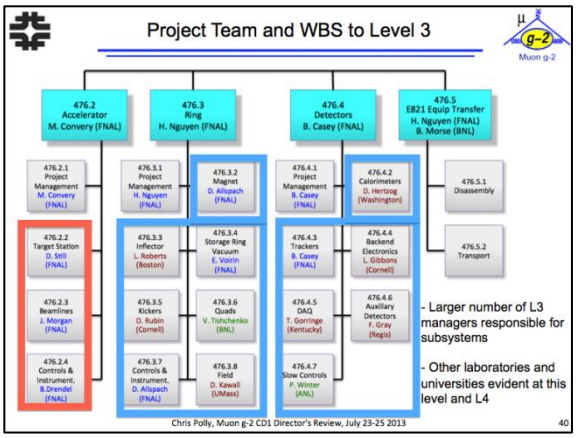
- The accelerator Bases of Estimate are very detailed for this stage of the project. The entries found in the document database are extensive with appropriate links between BoEs and back-up documents.

- The g-2 project team presented a clear picture of the scope of work, technical requirements and the plan to meet them, and detailed cost and schedule documents based on the technical plan. They are an experienced, motivated, and highly competent team.

- The development of an integrated management team, with the same people performing the same jobs on the project and the AIPs, in conjunction with senior laboratory management is a strong step in support of the program.

- As the accelerator portion is 60% of the overall g-2 project, it should receive that level of focus from project management. For example, at present, 13 L3 managers exist for the Ring and Detector, whereas 3 exist for the Accelerator.





Recommendations

1. Resource profiles for the accelerator work, specifically during shutdown periods, need to be generated by CD-1 and integrated with knowledge of AIP/GPP efforts during those periods.

2.2 Ring

Primary Writer: Matthias Perdekamp

Contributors: Louis Snydstrup

The muon storage ring and its complex inflector-, beam optics, control- and precision field measurement systems are based on the instrumentation used in the E821 experiment at Brookhaven National Laboratory. The E989 design for the ring systems improves and augments the existing systems from E821 so that the total systematic uncertainty for magnetic field measurement can be reduced to 0.07ppm. Detailed documentation of the design is available. The design is technically feasible and risks are well understood and documented. Value engineering has been carried out successfully; the use of the E821 ring significantly lowers the overall project cost and accelerates the project schedule. New and experienced collaborators from E821 have been integrated in a strong ring team for E989 and the E821 knowledge and lessons learned have been successfully transferred.

Since the past director's independent conceptual design review of the muon g-2 project from June 5-7 2013 the E821 superconducting coils have been transported successfully to Illinois. This was a remarkable feat engineered by FNAL and Emmert International. A detailed budget has been established; a thorough evaluation of the BoE has been carried out and carefully documented. ES&H aspects of the ring systems have been evaluated and documented. Measures to perform quality assurance have been identified.

2.2.1. Storage Ring

Findings

- The Muon g-2 experiment will re-use the BNL E821 storage ring magnet. The magnet has been disassembled. The superconducting coils with their cryostats have been transported successfully from BNL to Illinois and will arrive at FNAL the day following this review.

- A full assembly procedure for the yoke, poles, and cryostats has been developed, and provides a strong basis for cost estimating.

- A FNAL technician participated in the disassembly at BNL gaining important experience in the safe disassembly of the magnet, lifting procedures, and mechanical shimming.

- A FNAL person has been assigned the responsibility for the main magnet power supply.

- Risks have been identified. Specifically, the re-welding of superconductor has been mentioned, which must be carefully controlled to prevent overheating.

- Obtaining beneficial occupancy to the MC-1 experiment hall is on the critical path to reassembly, commissioning, and shimming the ring, which are expected to be time-consuming activities.

- BoE documentation is present and ES&H issues as well as QA have been addressed.

Comments

- ESH hazards have been identified, although they are not considered complete. Future reviews of the magnet system will inevitably involve aspects of pressure safety in cryogenic and vacuum systems and probably lifting safety.

- A long discussion took place during the review concerning the yoke/pole installation and the associated level of effort. This was a one year process at BNL, excluding precision alignment of the poles. A new metrology system has been budgeted for high precision alignment, especially for the poles. The cost shown in the Yoke BoE shows $70K plus 640 hours metrology technician testing /training. The system managers expected this system to usable by assembly technicians, enabling the magnet assembly to be more efficient and to be less dependent on the availability of survey technicians. The supervisor for the metrology group, on the other hand, expects to have a dedicated team for g-2.

Recommendations

2. For the Preliminary Design, the cryogenic and vacuum systems should be reviewed for pressure safety and include potential failure modes of cryogen leaks and loss of insulation vacuum.

3. The alignment and survey of the yoke and poles should be coordinated with the with the metrology group. The manpower estimates should be re-evaluated based on this common understanding of how the alignment process will proceed.

2.2.2. Controls & Instrumentation

Findings

- Controls and Instrumentation include cryogenic vacuum and vacuum pumps, coils, cryogenics, power supplies, and quench protection systems for the Storage Ring and Inflector magnets, about 500 instruments in total.

- E821 instruments will be tested and re-used if possible. However, for the readout a new modern PLC system will setup. The data recorded will be made available through a graphical user interface to operators and shift personnel.

- Following a suggestion from the June review, it was discussed to use the PLCs to capture coil voltage and temperature histories in case of a quench event.

- A low noise power supply for the inflector has been identified. Compared to E821 this will make it possible to significantly decrease the thresholds set to monitor for the loss of superconductivity in the inflector magnet.

- BoE documentation is present and ES&H issues as well as QA have been addressed.

Comments

- It was not apparent from the material presented how the cost associated with replacing faulty instruments has been determined. Time constraints did not allow inspecting the BoE for this detail during the review.

- The integrity of temperature probes on the coils and the nitrogen heat shield as well as the integrity of the voltage taps connected to the coils and interconnects are critical for temperature monitoring during cool-down and warm-up (difference of shield and coil temperature) and for the quench detection and analysis. It is important to test the relevant instruments as early in the project as possible.

Recommendations

None.

2.2.3. Beam Vacuum Chambers

Findings

- The Project plans to use the standard configuration E821 beam vacuum chambers. The effort will include the modification of the NMR trolley garage chamber for a straw trace back system.

- Two vacuum chambers will be rebuilt for E989 to achieve optimum integration of the beam tracking detectors.

- The funding and schedule appears to be appropriate for the defined tasks.

- BoE documentation has been provided and ES&H issues as well as QA have been addressed.

- Risks are considered to be low.

Comments

- The survey and alignment of the vacuum chambers was discussed with the metrology supervisor present during the Review. The vacuum chamber alignment is a multistep process of pre-survey of internal components followed by survey in the magnet gap and requires close coordination with collaborators responsible for other beam components and systems.

Recommendations

4. Develop a plan for using the new precision survey system in optimizing the vacuum chamber alignment as well as the trolley rails for the Preliminary Design.

2.2.4. Superconducting Inflector

Findings

- The existing inflector used in the BNL experiment will be reinstalled. The Project scope does not include a new inflector, although there is potential interest from Rutherford Lab to supply an inflector with significantly improved performance. Using the existing inflector provides considerable cost savings. However, compared to the new inflector design the number of stored muons will be lower by a factor 4.

- The existing inflector needs a new power supply (that has been identified) and needs repair of a leak.

- The funding and schedule appears to be appropriate for the defined tasks.

- BoE documentation has been provided and ES&H issues as well as QA have been addressed.

Comments

- It is not clear if the project is developing specifications and interfaces for a new inflector. The availability of these specifications would aid the development and installation of a new inflector once funding will have been secured.

- The risk to operation schedule and budget for a catastrophic inflector failure seems not well known and/or documented.

Recommendations

None.

2.2.5. Quadrupoles and Collimators

Findings

- The electrostatic quadrupoles and support frames (aka, cages) of the E821 experiment and the collimators will be refurbished and reused in E989. Most design changes are incremental and well within the performance boundaries for the systems established in E821. Most changes address lessons learned from g-2.

- The first outer quadrupole plates downstream of the inflector (Q1) exit window will be moved to larger radius to avoid multiple scattering of the injected muons, this will increase the number of stored muons by a factor 1.6. There will be a corresponding increase in quadrupole voltage in Q1 to 75 kV.

- An increase of the quadrupole HV from 25kV to 32kV will increase the CBO frequency and make it possible to separate CBO harmonics from the g-2 frequency.

- The change from half aperture collimators for E821 to elliptical full aperture collimators for E989 will reduce the muon losses to the required level.

- The original quadrupole/trolley frames were assembled using rails manufactured by an outside supplier that did not conform to the storage ring radius. This out-of-tolerance condition was compensated for during assembly with some loss of frame dimensional tolerance (and quad positioning). BNL has proposed a method to improve these frames further which will be verified first on a prototype. The costing includes this effort.

- Extensive BoE documentation has been provided and ES&H issues as well as QA have been addressed.

Comments

- Risks have been assigned to the possibility of not reaching the higher voltage and not meeting the alignment goals. In both cases the mitigation plan results in higher systematic uncertainties. Without a quantitative estimate of the increase in error bars it cannot be judged if the mitigation plans given provide acceptable alternatives.

Recommendations

None.

2.2.6. Kicker

Findings

- A new kicker design is being proposed by Cornell which will significantly improve the performance compared to the E821 kicker. The kicker plates provide more field per unit current and the square wave pulse network will reduce muon losses. A modified kicker chamber is also included in the scope of the project, which will reduce eddy current losses.
  .
- The increased kick of 14 mrad will allow changing the half beam collimators in E821 to full beam collimators in E989 as needed for better control of systematic uncertainties from beam losses.

- A kicker test stand has been prepared at Cornell University and first pulse shapes have been measured.

- BoE documentation has been provided and ES&H issues as well as QA have been addressed.

Comments

- Both the design for the kicker plates and kicker chamber are conceptual. A final configuration has not been tested and there is no evidence presented of successful

prototypes. The kicker plates will have to be integrated with a trolley rail design, and the chamber design could be challenging to manufacture.

- The use of faster thyratrons could provide a "flat-top" kicker field for the duration of a 120ns long bunch and eliminate systematic effects related to differences in the kick along the bunch. A kicker current with fast rise and fall time also would provide the option to eliminate the non-gaussian tails in the bunch structure by limiting the kick to the central gaussian.

Recommendations

None.

2.2.7. Precision Field

Findings

- The precision field measurement system will be upgraded from the unique system developed by Heidelberg and Yale for E821. The updated precision field measurement system will reduce the field uncertainty from 170 ppb in E821 to 70 ppb in E989.

- A field measurement team has been formed including collaborators from UMass, University of Washington, FNAL, Argonne and Oxford. The team as access to significant engineering resources at ANL, FNAL and the University of Washington. All available documentation and microprocessor codes from E821 have been collected. Recently the field team succeeded to secure direct consultation from the retired lead engineer for the E821 trolley system and the former E821 graduate student who was the E821 expert familiar with the trolley controls. Furthermore the E821 precision field leader has agreed to personally assist in restoring trolley system operations at BNL.

- A solution has been found for the replacement of components necessary for the maintenance of the custom electronics developed at Heidelberg University for the E821 NMR system.

- Following a recommendation from the June review it was decided to develop an additional water based absolute calibration probe. Oxford has developed plans for a third He-3 based absolute calibration probe and has applied for UK funding for this effort.

- Extensive BoE documentation has been provided and ES&H issues as well as QA have been addressed.

- The BoE justification is detailed. It is based on a thorough analysis of all sources of systematic uncertainties presented in the conceptual design review. The measures chosen to reduce E821 uncertainties to the error budget of E989 have been translated into realistic estimates for the effort needed. The improvements

evaluated include the quality of the trolley rails, the accuracy in the measurement of the trolley position, more frequent and more exact probe cross-calibrations, the use of modern field simulation techniques in support of the shimming operation, and the development of a second probe for absolute calibration.

Comments

- In order to achieve the best possible accuracy in the field measurement, E989 has invested in temperature control for the experimental hall, better thermal insulation of the magnet and increased stability of the floor that supports the magnet.

  Tolerance goals for the yoke construction, the pole and vacuum chamber positioning and trolley rail placement should align with the better field precision that will result from the improvements in the experimental hall.

- It is not clear if the budget presented reflects the cost to replace only faulty fixed NMR probes or all fixed probes (as suggested at the Director's Conceptual Design Review in June 2013).

Recommendations

5. Initiate a continuous effort to utilize the sophisticated survey system that will be setup for monitoring the yoke and pole piece installation for the systematic survey of all hardware relevant for the precision field measurement (yokes, poles, vacuum chambers, trolley rails, NMR probe positions, etc.). The analysis of such data will inform the assembly of all relevant ring systems, the shimming process and finally the precision field analysis.

2.3 Detectors

Primary Writers: Alan Hahn, Steve Kettell

Contributors:

Findings

- The Project only recently learned of the success of the NSF MRI for detector construction, allowing little time to develop a complete understanding of the contingency for the MRI.

- The Project plans to move the Calibration system, which may be provided by foreign collaborators, into the DOE base and treat the potential contribution as a risk opportunity.

- With the approval of the MRI, most of the detector has effectively reached CD-3 and with funds in hand, construction could begin. This allows a decoupling of the detector schedule from the CD milestones.

- The detector construction contains many possible funding sources: the MRI (for calorimeter, electronics and DAQ) is secure, the Early Career (for Tracker) is secure, the REU (for auxiliary systems) is secure, and the foreign contributions for the calorimeter calibration system and the tracker are not yet confirmed. The size of the DOE contribution is relatively small at $200k base cost.

- The Early Career (EC) base cost was shown as $1,172k. The quoted TPC for the tracker supported by EC is quoted at $1,736. The committee was told that the actual contingency held by the EC is $300k. The MRI total cost is $3.5M*0.92, but this includes some contingency. About half of the 8% reduction has been absorbed by reducing spares and half by off-loading electronics crates onto the DOE project. The REU base cost is of order $50k.

- Project management has recognized that some Installation and Integration activity is missing and has proposed to add some effort to the DOE Project, perhaps under Auxiliary Systems.

- The detector project expects to be on the critical path during some phase of installation after the initial magnet ring shimming.

Comments

- The Project recently learned of the success of the NSF MRI detector proposal; this is certainly good news.

- There appears to be significant undergraduate and graduate student labor that will be provided off-project that is not included in the resource loaded schedule.

- Prior to CD-1, the project management effort should be clearly included in the resource loaded schedule, even if as uncosted scientist effort.

- A "vendor quote" contingency category might be useful for the PbF crystal purchase. The 25% category for "vendor estimate" seems too high for a vendor quote. (Currency risk is and should be handled elsewhere.)

- For a variety of reasons managers did not take ownership of their contingency slides. This is not a good practice. All numbers and slides need to be owned by each manager.

- The review committee discussed with management several options for how to treat the contingency on the MRI scope. Two leading suggestions were 1) to treat the MRI detectors as an in-kind contribution with an appropriate DOE risk-based contingency or 2) to fully incorporate the MRI into the DOE project scope and treat the MRI base cost as the base cost and then to show two components of estimate uncertainty contingency – NSF and DOE.

- The presentation of the cost and contingency of this subsystem confused the committee.

- The committee commends plans to add Installation and Integration tasks and effort.

- The committee commends plans to put the Calibration system into the base cost, and treating this possible external contribution as a risk opportunity.

- We commend the joint and integrated management of the detector project (amongst various funding sources) and recommend that it continue, recognizing that part of the contingency will be held internally by systems receiving non-DOE-Project funding.

- The team has a lot of experience based on the previous experiment at BNL. The presentations did not emphasize this point very strongly. The detector design is likewise based on a very similar successful previous experiment. It would seem to be advantageous to emphasize this point as well. It is noted that the team's previous experience was clearly presented in the June's Director's Conceptual Design Review.

Recommendations

6. The Project should manage the NSF contribution as a fully integrated part of the g-2 project. The MRI base cost should be treated as part of the base project cost, and the estimate uncertainty contingency built from two components: one from NSF and one from DOE.

7. The project should review the base cost and contingency for the MRI and the Early Career award in order to develop the overall detector contingency in time for the CD-1 review.

8. Capture the student labor in the resource loaded schedule before the CD-1 review.

3.0 Cost and Schedule

Primary Writer: Lynda Gauthier

Contributors: Jeff Reiser, Jennifer Fortner

3.1 Cost

Findings

- The Muon g-2 project has a TPC range of $42.3M - $48.4M. This TPC range includes actual expenditures of $5.1M through May, 2013.

- The Muon g-2 project cost estimate is supported by detailed BOE documentation. The estimate includes all the project scope and is well organized by WBS. The total base cost estimate, excluding contingency, is $32.8M as shown below:

DOE	Fermilab Labor	M & S	Contract Labor	Total
476 Muon g-2	Base Cost	Base Cost	Base Cost	Base Cost
476.01 Project Management	1,538	696	673	2,907
476.02 Accelerator	11,106	7,343	351	18,799
476.03 Ring	3,097	2,722	758	6,577
476.04 Detectors	134	34	36	204
476.05 BNL Equipment Dissassembly & Transport	253	4,082	0	4,336
Grand Total	**16,129**	**14,877**	**1,817**	**32,823**

- Estimation uncertainty has been applied based upon the type of cost estimate (i.e. expert opinion, engineering estimate) for each line item in the cost estimate. Contingency percentages are defined in a guidance document titled, "Contingency Rules for Muon g-2". This document was provided to the estimators. The total cost estimation uncertainty is $9.5M. This represents 19.6% to 22.4% on the TPC range.

- The project calculated a risk range of $0.0M to $6.1M by applying a monte-carlo analysis to the risk registry and taking the 90% certainty values.

- The TPC range calculation as presented is shown below:

Cost Estimate	$32.8M
+Cost uncertainty	$9.5M
+Risk range	$0.0M - $6.1M
=TPC range	$42.3M - $48.4M

- The Muon g-2 project has multiple funding sources. The DOE funding covers the disassembly, transport and reassembly of the E821 equipment. It also provides for any upgrades related to the storage ring sub-systems or the magnetic field. A

$3.5M NSF MRI provides the majority of the funding for the calorimeters, electronics and DAQ. An Early Career grant provides funding for the construction of tracking changers. Further in-kind contributions are being negotiated.

- The obligation profile presented at the review exceeds the current funding guidance. The Committee was advised by the agency that updated guidance will be provided following the CD-1 review.

Comments

- The majority of the cost estimators are Control Account Managers on the project and they demonstrated ownership and accountability of their cost estimates.

- The cost estimating system itself is quite impressive with respect to its structure, organization, level of detail and user interface.

- After conducting drilldown exercises within the Basis of Estimate documentation and tracing items from BOEs to the P6 schedule, the Cost and Schedule subcommittee maintains an 85% confidence level in the Muon g-2 project base cost estimate.

- The project is exercising configuration management with a change log on the cost estimate which is commendable.

Recommendations

9. Re-evaluate the contingency "type of estimate" values assigned to the estimate particularly those assigned to "expert opinion - 60%". Update estimates for any quotations in hand.

10. Summarize the cost estimate by the type of estimate (i.e. Documented Vendor Estimate Based on Drawings/ Sketches and Specifications, Expert Opinion – High Confidence) in a chart or table to present at CD-1. This will allow the project to demonstrate the continued maturity and refinement of the estimate over time leading up to CD-2.

11. Level the obligation profile to fit within the current proposed funding authorization profile up to and including FY16.

3.2 Schedule

Findings

- A schedule has been created in P6 containing 1,678 activities starting October 2012 and completing in December of 2017. The schedule is broken down into WBS elements for Project Management, Accelerator, Ring, Detectors, and BNL Equipment Disassembly & Transport. Work packages are included for the Preliminary Design. Final Design and Implementation are included as planning packages.

- The activities are loaded with resources (labor and M&S) that typically match what is in the BOE. There are some instances where the labor hours and non-labor costs do not match. Uncosted resources are not fully defined. All the schedule resources are loaded with a linear profile, regardless of whether it is a planning package or a work package.

- Interface Milestones are included for key points to other projects; MC-1 High Bay, End of Circulating Beam Studies, Cryo plant ready to cool g-2, Beamline Enclosure Beneficial Occupancy, Primary Beam Transport Complete, Recycler RF Complete, and Delivery Ring Complete. These milestones are not directly linked to other projects but will be updated on a regular basis. Not all the milestones are directly tied to activities within the g-2 schedule.

- Project milestones: The milestone dictionary lists over 500 milestones showing WBS, level, description and definition. Most give a good definition of what is needed to achieve the milestone, but for some milestones the definition is just a copy of the description. The Preliminary PEP (PPEP) calls out Critical Decision Milestones, defined as L0. The PPEP calls out Level 1 and Level 2 milestones as "will be added prior to CD-2". The P6 schedule has L4 CD milestones and L5 milestones for start and completion of level 4 WBS work packages and planning packages.

- The schedule does not have a defined critical path to completion.

Comments

- The addition of higher level milestones into the schedule will provide definition for the schedule contingency.

- Allowing more of the project team/CAMs to access the schedule information would increase the level of data integrity.

- Development of the implementation phase of the schedule and updating the cost profile on planning packages will provide refinement to the cost plan.

- It would be beneficial to know what the status of the project is to date as it relates to the $5.1M spent through May 2013, i.e., what work has been completed to date vs. the work planned to date.

- Including all the uncosted resources in the schedule will provide a more complete picture of FTE requirements.

- Without the schedule showing a critical path, the project team can only estimate that a deviation on an activity will affect the project completion.

Recommendations

12. Further develop the implementation portion of the schedule to the extent that a critical path can be defined.

13. Further develop the milestones making sure they are consistently defined throughout project documentation (Dictionary, PPEP, P6 Schedule, Presentations). Consider developing a separate formal (with signatures) interface milestone document that clearly defines the deliverables for each key interface milestone.

4.0 ESH&Q

Primary Writer: Mike Andrews

Contributors: Halley Brown

Findings

- The Project has identified W. Merritt, the Deputy Project Manager, as the ESH Coordinator.
- The Project Management Plan appropriately addresses the responsibilities of the ESH Coordinator.
- A Preliminary Hazard Analysis Report has been developed in draft form and addresses the hazards related to the Project at this phase.
- The Project ISM Plan is defined in Section 14 of the Project Management Plan.
- The Project Quality Assurance Program is globally addressed in Section 10 of the Project Management Plan.
- The Project presently has not identified a Project Quality Assurance Coordinator.
- The general Safeguards and Security requirements have been identified in the Preliminary Project Execution Plan and the Project Acquisition Strategy document. The Project will create no new security risks or requirements.
- A NEPA Categorical Exclusion was issued by DOE-FSO Site Manager on December 20, 2012.
- The Project developed a comprehensive Quality Assurance Plan for the transport of the ring to Fermilab.
- Each L2 presenter incorporated an ESH component into their plenary presentation slides.
- Project MOU's include flow down of Fermilab ESH&Q requirements.

Comments

- The current Deputy Project Manager position is also the ESH Coordinator. The Deputy Project Manager position is not planned to exist after CD-3 approval. A plan should be understood as to how the ESH Coordinator responsibilities will be managed by the Project including the option of possibly sharing FTE costs with both Mu2e and Muon Campus Projects.
- The Preliminary Hazard Analysis Report should be scrubbed to address missing data and question marks. The PHAR should also more specifically address

beamline and detector control/operations responsibilities, and the Accelerator Readiness Review process. Remove references to Preliminary Safety Assessment Documents (PSAD). Also modify the document title to reflect CD-1 requirement.

- The Project Management Plan should address the responsibilities of the Project QA Coordinator and the Installation Coordinator positions.

- The Project Schedule should include ESH/QA milestones eg. development of Safety Assessment Documentation and the Accelerator Readiness Review requirements.

- All L2 Project presentations slides should include a QA component.

Recommendations

14. Develop an approved Preliminary Quality Assurance Plan (PQAP) by CD-1.

15. Appoint a Quality Assurance Coordinator and define responsibilities in the Project Management Plan.

16. Finalize and approve the Preliminary Hazard Analysis Report by CD-1

5.0 Management

Primary Writer: Ken Stanfield

Contributors: Nancy Grossman, Mike Dinnon

Findings

- The project is led by Project Manager Chis Polly and Deputy Project Manager Wyatt Merritt. All Level 2 managers and Level 3 managers have been identified and are in place.

- The project organization parallels the WBS structure and is therefore aligned with project deliverables.

- The success of the g-2 Project depends on the success of a series of AIP and GPP projects called the Muon Campus Program.

- The Level 2 Accelerator project cost estimate represents ~57% of the total project base cost. The L2 Accelerator manager is also Coordinator for the $55M Muon Campus Program carried out by the Accelerator Division as AIP and GPP projects. There are a number of mechanisms in place, such as a PMG, the POG, and interface milestones, to assist in the coordination of the Muon Campus Program and the g-2 Project.

- Much of the labor for the project is provided by Fermilab through its Divisions using a matrix approach.

- Elements of a staffing plan, such as labor profiles over the life of the project were presented.

- KPPs, both threshold and stretch goals, have been defined. The project plan as represented in the base estimate is designed to achieve threshold goals.

- The current DOE base cost estimate is $32.8M. A 34% contingency on costs to go of $27.7M is based on a maturity of design approach estimated in a bottom up manner.

- The total Project Management Cost Estimate is $6M with a 20% contingency of which about ½ supports the Project Office. This is judged to be reasonable.

- Early project completion was presented to be the end of Q3FY16.

- The project management tools P6 and Cobra are in use to support project managers when making decisions.

- The range of costs proposed by the project at this review is $42.3M – $48.4M. This range is determined by the 90% confidence limits on the distribution of

possible risk cost outcomes added to the base estimate plus the bottom up contingency.

- The project is to be commended for the significant value engineering effort they have made by re-using many components and for incorporating lessons learned from previous projects.

- The Muon g-2 Configuration Management Plan describes the process of the Project Manager being a signatory to change requests involving the Muon g-2 and Muon Campus interface milestone dates. The appendices covering the Requirements Documents and Interface Milestones with the Muon Campus are blank. There are three interface milestones critical to the Muon g-2 project schedule.

- The project would like to start D30 reconfiguration work in FY14, which requires CD-3.

- Some risks will be retired and BOE contingency estimates reduced by CD-2.

- The Deputy Project Manager position is not budgeted past the approval of the CD-3 implementation phase of the project.

- The Project Manager is fulfilling the Risk Manager role.

- The Project team presented a Risk Management Plan describing the process for managing risks for the Project.

- The Project has completed an initial risk assessment and documented the results in the Project Risk Register. Threats and opportunities have been addressed in the Risk Register.

- Concerns were expressed by the Project as to whether staffing support from Divisions will be provided when it is needed. There is a risk addressing this in the Risk Register.

- The Project presented a list of documentation deliverables for CD-1.

- Value Engineering is documented in the CDR.

- There is not a standalone assumptions document. The committee was referred to the Contingency Rules document and the Cost & Schedule Range Methodology document (Reviewers' Guide for CD-1 Director's Review - Part II).

- Interface milestones for the deliverables from the Muon Campus AIPs and GPPs have been developed. The g-2 Project Manager will monitor progress with Muon Campus monthly reports and PMG (Project Management Group) meetings. An internal review conducted in early July recommended that the approval of the g-2

Project Manager be required when a change in schedule of any interface milestone date affects the g-2 project.

Comments

- The Management team is a strong one with relevant experience with g-2 and with the accelerator systems that are needed for the project. This team is capable of successfully completing the project.

- Fermilab understands the advantages and risks of managing the Muon Campus Activities and is working to ensure success of the integrated program. They recognize the need to manage the interfaces and dependencies and have processes in place to do so.

- The current base cost estimate of $32.8M seems complete, and reasonable. A 34% contingency ($9.5M) on cost to go ($27.7M) based on estimation uncertainty (maturity of design) has been developed in a bottom-up approach. A Monte Carlo of possible risk cost outcomes yields a distribution whose mean is ~$3M and whose 90% confidence level limits are $0M to $6.1M. If the project were to take the mean as a top down risk based contingency estimate, then the current estimate for the DOE TPC would be $45.3M which includes a total contingency on costs to go ($27.7M) of $12.5M (45%). This committee believes that a 45% contingency at this stage of the project plan development is reasonable.

- To improve communications and planning the labor resource for the project, the Project should consider executing annual MOUs with laboratory divisions which states the purpose of the labor; identifies the labor resources amount and type needed by the project; and their source.

- While a schedule was presented, the current level of schedule development does not give high confidence either in the schedule, its end date, or the cost contingency associated with risks in successfully achieving it.

- The plenary presentations each had similar content which focused on what the committee needed to focus on for CD1; including scope, organization, cost and schedule.

- Components that are re-used and thus have zero cost should none-the-less carry contingency based on the possible need for re-work of the items. The project should review the list of recycled items and appropriately add contingency and schedule for re-work/refurbishment/replacement.

- Planning packages should be broken down to the extent that a critical path for the project can be determined. This would allow one to look at the risks associated with the critical path and better determine how they might impact the project completion date and cost.

- The project should have a Deputy Project Manager throughout the life of the project. This key position is important for supporting the Project Manager to ensure project success.

- A general cleanup of the Risk Register should be completed to remove overlaps in uncertainty and to add important items discussed with the project Team at this review.

- It is recognized that implementing initial risk identification during the BOE process is an excellent proactive practice.

- Staffing risks should be associated with the appropriate parts of the project, focusing on those areas of concern such as tasks requiring key personnel and/or high levels of a particular resource; i.e. mechanical technicians.

- The Assumptions document should be a standalone document that includes overhead rates and what is to be delivered by GPPs, AIPs, NSF, etc. This document can be based on other Fermilab project Assumptions documents and point to other documents that contain relevant information as appropriate.

- Taking credit for past Value Engineering and future plans for it would be better presented in a standalone document.

- Milestones, especially those reported to DOE or associated with off project items (GPPs, MRI, etc.) need to be clearly defined so that the responsible person can unambiguously determine when it has been completed.

- An ESH&Q incident risk should be added to the risk register with an appropriate probability of occurrence to show the importance of this HIGH impact risk event.

- Obtain all signatures for documents prior to the DOE CD-1 Review.

- Prior to the CD-1 review all CD-1 documentation should be updated to include placeholder information such as Life Cycle Costs in the Acquisition Plan and information that comes from changes following this review.

- The Project schedule delay risk items should be separated in the risk register to allow for more concise analysis on individual items.

- The requirements documentation will better serve the Change Management process if it is traceable and shows ‘parent’ and ‘child’ relationships.

- The PEP is an agreement between the Laboratory, the Project and the DOE, delineating what the Project will deliver for the funding provided. It should focus on the DOE deliverables and their realization. The Project, in consultation with Laboratory and the DOE, should consider basing the PEP, including the KPPs, only on DOE deliverables.

- The Project, DOE and the Laboratory need to be come to a consensus on appropriate KPPs for the project.

- The project should investigate forward funding opportunities with collaborating institutions as a means of ameliorating the effects of potential funding delays.

- The project should write an Assumptions document for the project by the DOE CD-1 review.

- The project should update the milestone dictionary with more detailed, clearly defined completion descriptions by the CD-1 review.

Recommendations

17. Ensure that the Project Manager has a deputy with project management experience for the duration of the project. Similarly, there should be a named person or persons to coordinate ES&H and QA for the duration of the project.

18. Prepare a Staffing Plan to include labor requirement profiles by type and the identification of the source of this labor.

19. Complete the Muon g-2 Project Configuration Management Plan and implement at least the portions related to the Muon Campus interface by the CD-1 review.

20. Prepare a more mature linked RLS for CD-1, which would add quantifiable credence to a critical path, float, and the end date.

21. Review/update the risks associated with the critical path; add staffing risks associated with key personnel needs and high level resource needs to appropriate portions of the project schedule by the CD-1 review.

22. The project should refine its understanding of remaining risks, listing those that will be retired prior to the projected CD-2 date and present this at the CD-1 review. This information should be used to prepare a current point estimate, including contingencies (the current TPC estimate), which should then be used as the primary basis for presentation of the cost estimate and the development of the cost range.

23. Develop and present lists of possible options for both scope increases and scope reductions to be exercised in the event of good or adverse cost experience respectively.

24. Pursue CD-3a in the event that a formal CD-2 baseline cannot be achieved in FY14.

25. Considering the current maturity of the cost estimate and schedule development the committee recommends a cost range of from $39.6 to 49.4M as one that would

include possible cost outcomes for the project with an appropriately high probability.

26. Proceed to the CD-1 DOE review after addressing recommendations from this review.